

A Dedicated Experiment to Measure the Muon
EDM in a Storage Ring

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Outline

- Introduction
- Theoretical motivation
- EDM Measurements with Storage Rings
- Previous measurements: muon EDM from g-2 experiments
- Proposed new approach: freeze Magnetic Dipole Moment spin precession in a ring
- Plans
- Conclusions

Barion asymmetry of universe needs new sources of CP violation

CPT invariance $\rightarrow CP$ violation

$EDM \neq 0 \rightarrow P$ and T violated.

$$\begin{bmatrix} P \\ C \\ T \\ \bar{C} \\ \bar{T} \\ \bar{P} \end{bmatrix} = \begin{bmatrix} + & - & - & + \\ - & + & + & - \\ + & - & + & - \end{bmatrix} \begin{bmatrix} E \\ B \\ \bar{E} \\ \bar{B} \\ d \\ \bar{d} \end{bmatrix}$$

Transformation properties:

$$H = -\vec{d} \cdot \vec{B} - d \cdot \vec{E}$$

Electric and Magnetic Dipole Moments

Current Experimental Limits on EDMs

$$d_n = -1.0 \pm 3.6 \times 10^{-27} e \cdot cm, < .63 \times 10^{-25} e \cdot cm \text{ (90% CL)}$$

SM: $10^{-32} - 10^{-31}$

$$d_p = 3.7 \pm 6.3 \times 10^{-23}$$

$$d_{^{199}Hg} = -1.06 \pm 0.49 \pm 0.40 \times 10^{-28}, < 2.1 \times 10^{-28} \text{ (95% CL)}$$

$$d_e = 0.69 \pm 0.74 \times 10^{-27}, < 1.6 \times 10^{-27} \text{ (90% CL)} \quad \text{SM: } < 10^{-41}$$

$$d_\mu = 3.7 \pm 3.4 \times 10^{-19}, < 1.1 \times 10^{-18} \text{ (90% CL)} \quad \text{SM: } < 10^{-38}$$

$$(\text{CERN III Statistical: } \pm 2.7 \times 10^{-19} e \cdot cm, \text{ Systematic: } \pm 2 \times 10^{-19} e \cdot cm)$$

Electric Dipole Moments

Current EDM experimental limits are far larger than SM

predictions

Non-zero EDM: Unambiguous evidence for new physics

← New source of CP violation

- d_μ : crucial to understanding nature of the source of EDM.
- Only accessible EDM outside first generation
- A number of theories predict $d_\mu > 10^{-24}$
- $d_e \approx 10^{-28} \approx 10 \times$ less than current exp't. limit.
- w/seesaw mechanism + large neutrino mixing, $d_\mu \approx 5 \times 10^{-23} \text{ e.cm}$, -Babu, Dutta, Mohapatra, PRL 85, 5064(2000): L-R symmetric
- e.g. $d_\mu \approx \text{few} \times 10^{-23}$
- Easy to get non-conventional scaling in supersymmetry:
terms.
- Assumption of universality of scalar masses, proportionality of A
prediction of SM and some of simplest theories, e.g. MSSM with
 $d_\mu = \frac{m_e}{d_e} = 1.4 \pm 1.5 \times 10^{-25}, < 3.3 \times 10^{-25}$ (90% CL).
- With **conventional scaling**,

New experiment goal: $\varrho d_\mu \approx 10^{-24} - 10^{-26} \text{ e.cm} \rightarrow \times 10^6 - 10^8$ improvement over current limit

Proposed Measurement of the Muon EDM

Connection to Magnetic Dipole Moment : general dipole moment

operator

$$LD_M = \frac{1}{2} [D_{\mu_0}^{\alpha\beta} \frac{1+\sqrt{5}}{2} + D_*^* \bar{\mu}_0^{\alpha\beta} \frac{1-\sqrt{5}}{2}] u_F^{\alpha\beta}, \text{ where}$$

$$d^\mu = \frac{e}{2m\mu} R e D, \quad d^\mu = Im D$$

Define $D_{NP} = |D_{NP}| e^{i\phi_{CP}}$, $a_{NP} = a_{exp}^\mu - a_{SM}^\mu$,

'New Physics' implied by $a_{NP} \neq 0$ can induce an EDM:

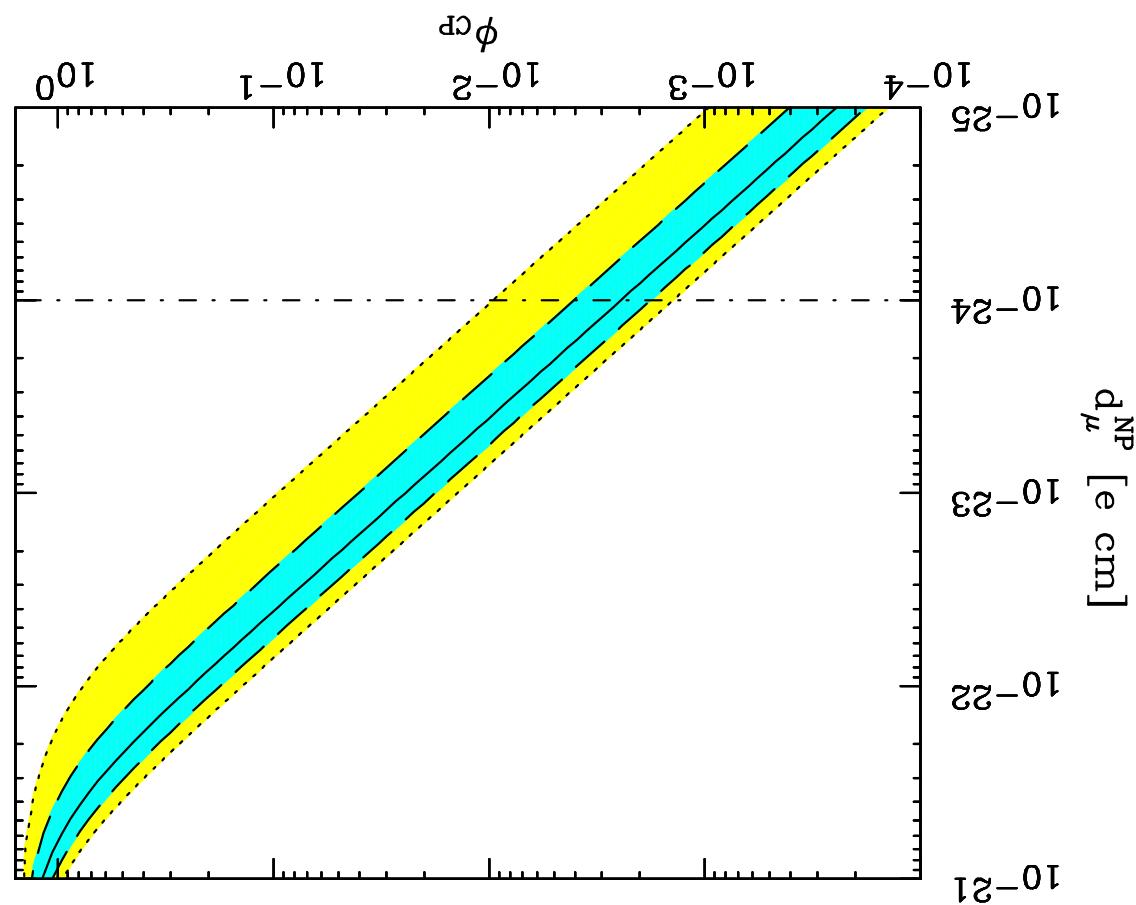
$$d_{NP}^\mu \approx 3 \times 10^{-22} \left(\frac{3 \times 10^{-9}}{a_{NP}^\mu} \right) \tan \phi_{CP} \text{ e} \cdot \text{cm}$$

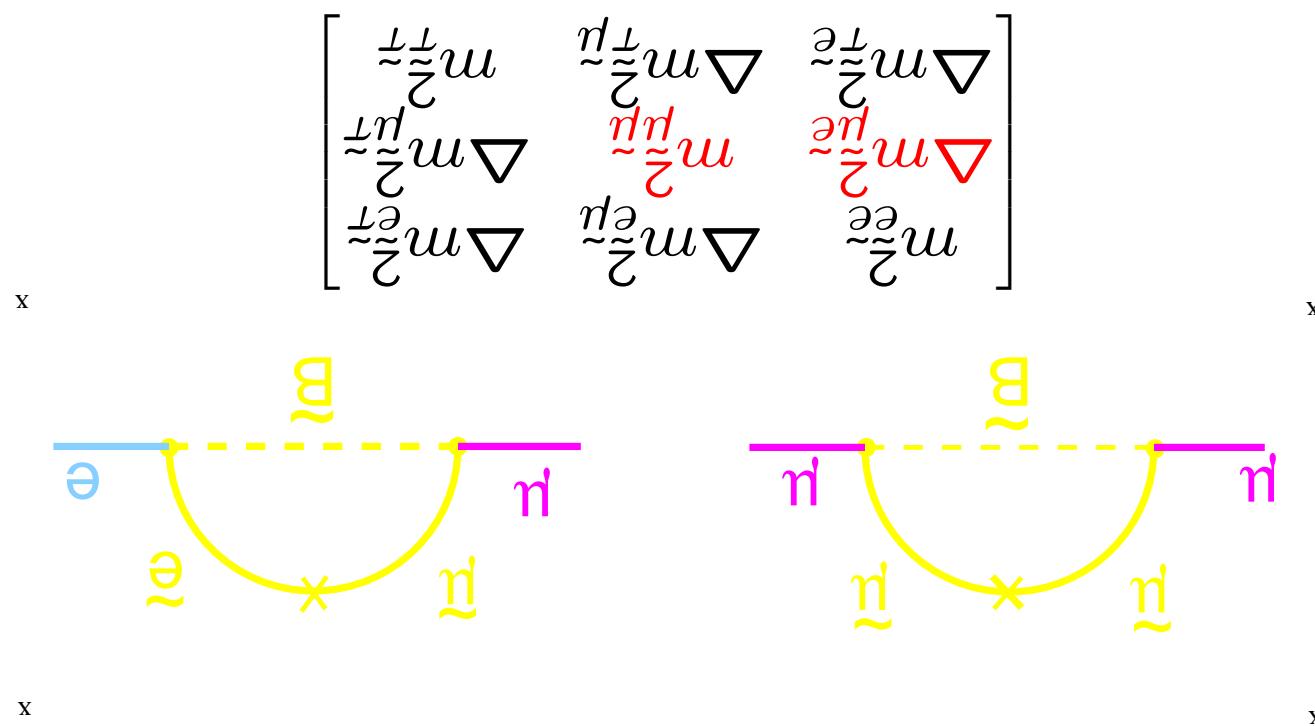
$$a_{NP} = a_{exp}^\mu - a_{SM}^\mu \approx 3(1) \times 10^{-9} \xleftarrow{d_{NP}^\mu \approx 3 \times 10^{-22} \tan \phi_{CP}} \text{ e} \cdot \text{cm}$$

$$d_\mu \approx 10^{-24} \text{ e} \cdot \text{cm} \text{ probes } |\tan \phi_{CP}| > 3(1) \times 10^{-3}$$

[Feng, Matchev, Shadmi, NP B613, 366(2001)]

$$d_{NP}^u \approx 3 \times 10^{-22} \left(\frac{3 \times 10^{-9}}{a_u^u} \right) \tan \phi_{CP} e \cdot \text{cm},$$

1 o and 2 o bands for $a_{NP} = a_u^u - a_{SM}^u \approx 3(1) \times 10^{-9}$ 



SUSY Connection among d_u , a_u , and $\mu \rightarrow e$

- Potential sources of EDM:
- neutron, proton, P- and T- odd nuclear force
- Nuclear physics is fairly straightforward
- For EDM(deuteron) $\approx 10^{-27}$:
- No Schiff suppression of nuclear EDM as in ^{199}Hg ($10-100$ times more sensitive to P, T odd nuclear force than current neutron value) (Khriplovich and Korkin)
- Competitive with planned future limits on P,T odd nuclear force from neutron and ^{199}Hg
- Crucially complementary to neutron and electron in determining source of EDM

New experiment goal: $qd_{deut} \approx 10^{-27} e \cdot cm$

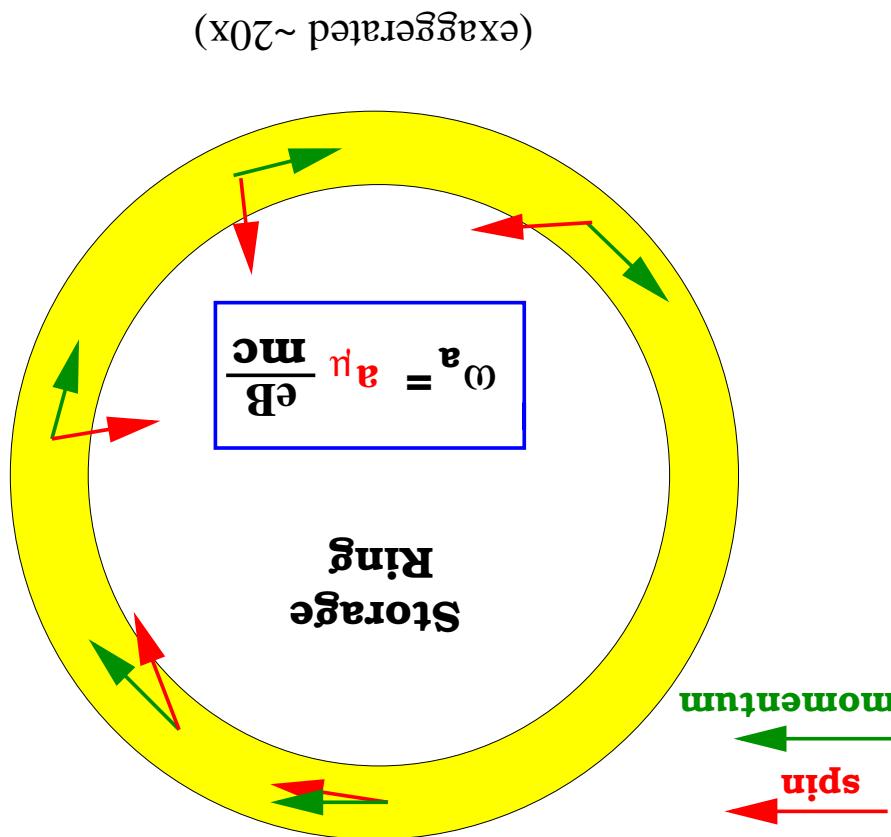
An Aside: Using Storage Rings to Measure the Deuteron EDM

Using Storage Rings to Measure EDMs

BNL

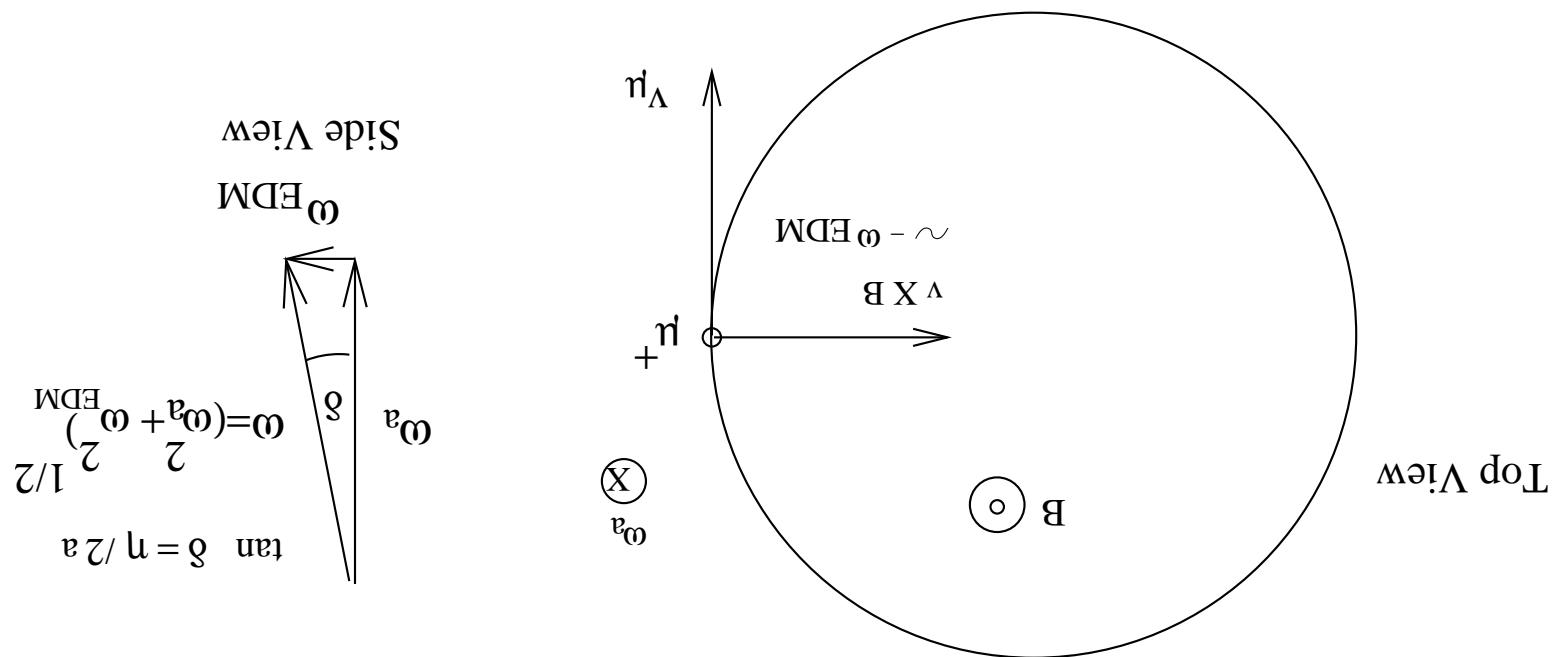
I. Methods used in previous muon g-2 expts at CERN and

II. Proposed **new** method for a dedicated muon EDM Expt.



g-2:
Simplified picture
No $E\leftarrow$
No EDM

g-2:



Choose γ so that $-a_u + \frac{\gamma^2 - 1}{2} \approx 0$; Note: $S^z = S_{\text{edm}} \frac{\omega}{\omega_{\text{edm}}} \sin \omega t$

$$\text{where MDM} = (1 + a_u) \left(\frac{e\hbar}{2mc} \right), \text{ EDM} = d_u = \frac{\alpha}{2} \left(\frac{e\hbar}{2mc} \right)$$

$$\omega = -\frac{m}{e} [a_u \vec{B} + (-a_u + \frac{\gamma^2 - 1}{2}) \vec{E} + \frac{a}{c} (\vec{B} \times \vec{E} + \vec{E} \times \vec{B})]$$

Spin Precession with \vec{B} and \vec{E} and an EDM

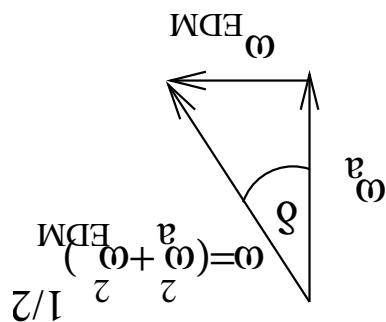
Measurement of Muon EDM in (g-2) Experiments

- Method I. Assume discrepancy with SM, $\Delta\omega = \omega - \omega_{SM}$ is due entirely to non-vanishing a_u rather than to a new physics shift in a_u .

$$\omega = \sqrt{\omega_{SM}^2 + \omega_{EDM}^2} \rightarrow \omega_{EDM} = \sqrt{\omega^2 - \omega_{SM}^2}$$
 - Worked well for CERN: large $\frac{a_u}{\omega a_u} = 7ppm$, a_u consistent w/ SM
 - Not well suited to BNL g-2 expt: small $\frac{a_u}{\omega a_u} = .7ppm$, a_u NOT consistent with SM within errors, giving poor limit on a_u
 - Method II. $d_u \neq 0$ causes $\tilde{\omega}$ to tip by angle δ in radial direction away from vertical

$$\tan \delta = \frac{2a_u}{\tilde{\omega}} \propto d_u \quad (d_u \approx 7 \times 10^{-14})$$
 - p_z of decay electrons oscillates at frequency $\omega \leftarrow$ oscillation in average vertical position of electrons at the detector vs time (both proportional to d_u)

Methods Used by CERN III, BNL g-2 Expts.



1×10^{-19} with equal Stat. and Syst. errors.
 BNL g-2: Anticipate improvement of x3-5 over CERN III, i.e. $a \approx$

- Timing offsets
- Energy calibration of detectors
- Detector tilt
- Beam position
- Correct by aligning detectors with centroid average vertical beam
- Detectors \leftarrow false EDM signal.
- Troids + spin dependence of vertical width of electron dist. at troids
- Vertical misalignment between beam and detector vertical centroid by aligning detectors with centroid average vertical beam

Systematic Issues

$$\text{CERN III: } d_u = 3.7 \pm 3.4 \times 10^{-19} e \cdot \text{cm}, \delta = \frac{\omega_{EDM}}{\omega_a} \approx .5 \times 10^{-2}$$

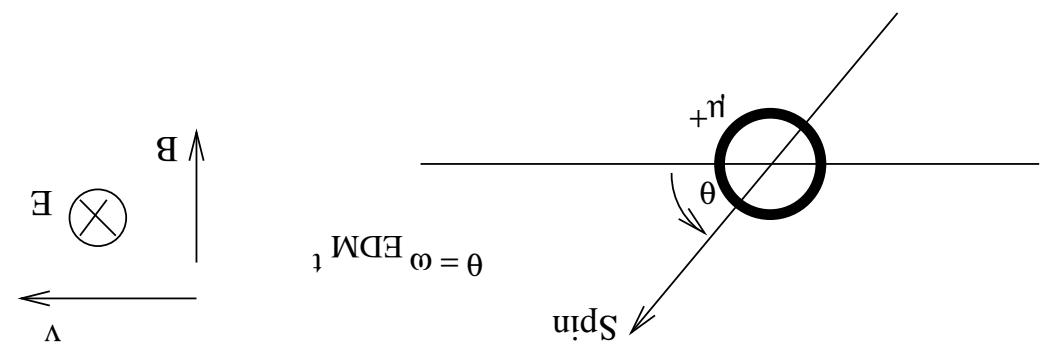
$$R_N = \frac{N_{up} + N_{down}}{N_{up} - N_{down}}, N_{up,down} = \# \text{ electrons above, below mid-plane}$$

Method II (Cont'd): Up-Down Oscillation of Decay Electrons

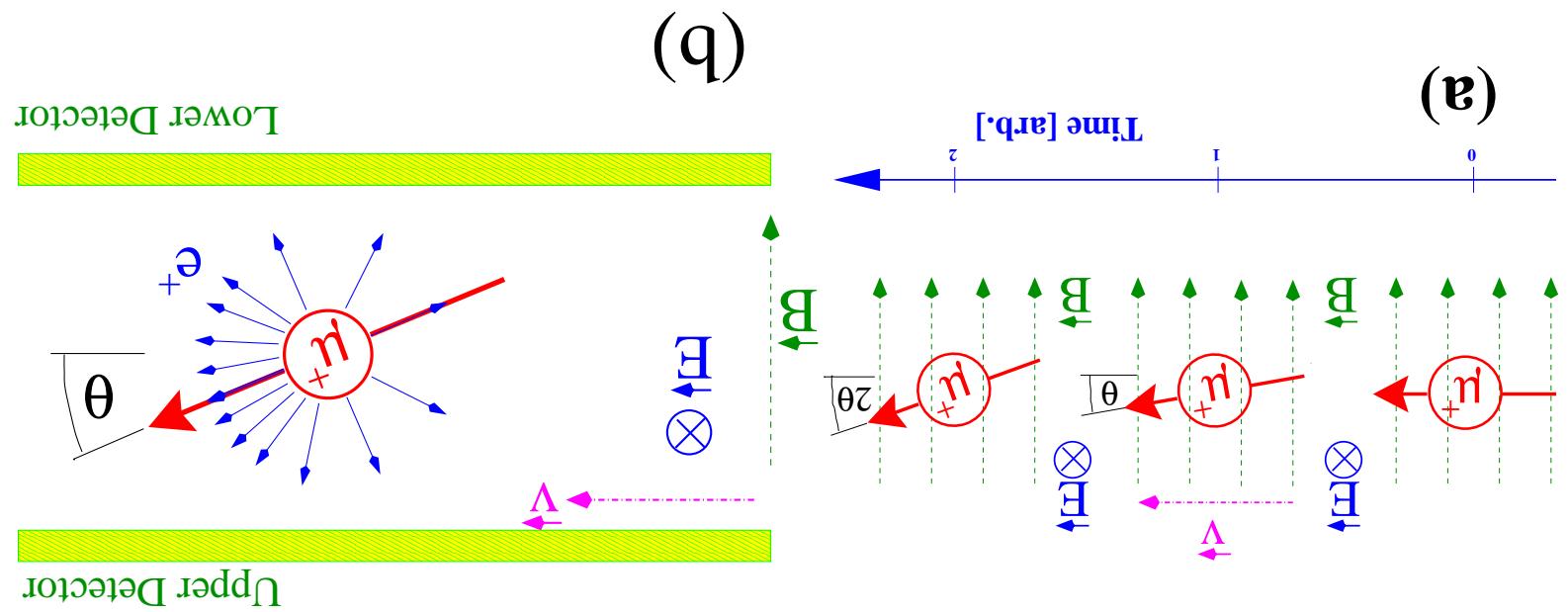
The Muon EDM Collaboration

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Boston University J. Miller - A Dedicated Experiment to Measure the Muon EDM in a Storage

- Focus beam with gradient B -field
 $(\text{Before: } \delta \approx 10^{-2} \text{ New method: } \theta \approx 1 \text{ after } 1\tau)$
 $S^z = S_{\omega edm} \sin \omega t \leftarrow S^z \approx S_{\omega edm}$
 siion background, precession directed radially.
 - Result: Large enhancement of EDM signal relative to g-2 precessio-
 n. Only precession due to EDM remains: $\omega_{EDM} = -\frac{m}{e} \gamma (\vec{E} + \vec{\beta} \times \vec{B})$
 (N.B. $\vec{\beta} \times \vec{B} \ll \vec{E}$ term in ω_{EDM})
 - to zero: $E_r = \frac{a_u C B_z}{\gamma^2 - 1 - a_u} \beta_\theta \approx a_u B C \beta_y^2, E_z = 0, B_r = B_\phi = 0$
 - Choose γ , \vec{B} and \vec{E} so that precession due to first two terms sums
- $$\omega = -\frac{m}{e} [a_u \vec{B} + (-a_u + \frac{1}{\gamma^2 - 1}) \vec{\beta} \times \vec{B} + \frac{c}{\gamma^2 - 1} (\vec{\beta} \times \vec{B} + \frac{c}{E})]$$



Signals



Muons: $R_N(t) = \frac{N_{up}(t) + N_{down}(t)}{N_{up}(t) - N_{down}(t)}$ or $R_E(t) = \frac{E_{up}(t) + E_{down}(t)}{E_{up}(t) - E_{down}(t)}$

Deuterons: $R_N(t) = \frac{N_{right}(t) + N_{left}(t)}{N_{right}(t) - N_{left}(t)}$

year of running
with PRISM-II, available from J-PARC (1 MW proton beam) - one
Muon: $q_d^u = 10^{-24} e \cdot cm$, $A = 0.3$, $P = 0.4$, $\rightarrow N \approx 4 \times 10^{16}$ Example:

For $B = 0.25 T$, $p \approx 0.5 \text{ GeV}/c$

- Subject to constraint on B , E , γ : $E_r = \frac{(1-a_u)B_\theta}{a_u B_z} < 2 \text{ MV/m}$
- Maximize $P\sqrt{N}$, B , p

To minimize statistical error

m = mass, p = momentum, P = polarization, A = asymmetry of vertical decays, N = number of detected electrons, τ = rest lifetime (muon, $2.2 \mu s$), B = B-field.

$$q_d = \frac{2\sqrt{2\tau u BAP\sqrt{N}}}{h_m} = \frac{2\sqrt{2\tau p BAP\sqrt{N}}}{h_m}$$

Statistical error on EDM

Potential Systematic Error Due to $\langle E^z \rangle \neq 0$

Recall $\tilde{\omega} = \omega_a + \omega_{EDM}$, where

$$\omega_{EDM} = -\frac{e\eta}{2m} (\vec{B} \times \vec{E}) = -\frac{e\eta}{2m} (\vec{B} B^z + \frac{e}{c} \vec{E}^z) \quad \text{a } \vec{E}$$

Non-zero B^r and E^z lead to non-zero $(\omega_a)^r \rightarrow$ False EDM signal

$$\langle E^z \rangle = 0 \rightarrow B^r B^r = \frac{e}{E^z}$$

This gives: $\tilde{\omega}_a \leftarrow -\omega_a$, $\tilde{\omega}_{EDM} = +\omega_{EDM}$

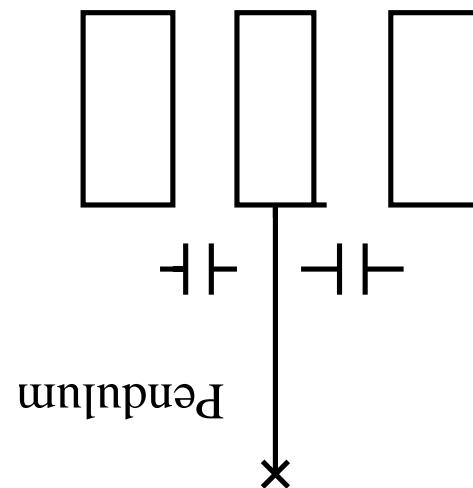
To control false EDM: $CW \rightarrow CCW$: $\vec{B} \leftarrow -\vec{B}$, $\vec{E} \leftarrow \vec{E}$

This is the largest potential source of systematic error

$$(a_u \vec{B} + (-a_u + \frac{1}{2-1}) \vec{B} \times \vec{E}) = (a_u B^r + (-a_u + \frac{1}{2-1}) B^\theta E^z) \approx \frac{B^\theta}{E^z} \vec{B}^r$$

Radial component of ω_a is given by

- Fabry-Pérot interferometer monitors electrostatic plate movements.
sign, ω_{EDM} does not.
- Inject muons CW and CCW in ring: ω_a (false precession) flips



- Align \vec{E} electrodes then monitor with inclinometers

In practice:

Handling the non-planar E-field

T_{21} correction

Deuterons: Up-down counters monitor beam stability, precession, give

Muons: Left-right counters monitor beam stability, precession

CW and CCW storage will cancel effect.

Main issues: gain stability vs. time, beam position movement vs. time

$$R^N(t) = \frac{N^R(t) + N^L(t)}{N^R(t) - N^L(t)}$$

Deuterons

$$R^E(t) = \frac{E^{up}(t) + E^{down}(t)}{E^{up}(t) - E^{down}(t)}$$

Muons

Systematic Error from Detectors and Stored Beam Instability

Remarkably, similar ring setup for both Muons and Deuterons!

E-field needed to cancel w_a : $E_r \approx B_{zcp}(a \frac{m}{\lambda})$

For $p \approx 500 \text{ MeV}/c$,

Muon: $a = 0.001166, \gamma \approx 5, m = 0.105 \text{ GeV}/c, a \frac{m}{\lambda} = 0.054$

Deuteron: $a = -0.143, \gamma \approx 1, m = 1.876 \text{ GeV}/c, a \frac{m}{\lambda} = -0.076$

Most design principles apply to both u and d EDM rings

Major(and promising!) deuteron ring development effort now under way for use at BNL or some other deuteron source. Mount and complete deuteron EDM measurement in 6 years after funding...

Proposed Muon EDM Experiment

- Muon Storage ring
 - $E \approx 2\text{MV}/m$, $B \approx .25\text{T}$, $p \approx 500\text{MeV}/c$, $\frac{d}{\Delta p} < 2\%$
 - Strong magnetic focusing
 - Inject CW and CCW to control systematic errors
 - Polarized, pulsed, high flux sources
 - Example: J-PARC+PRISM-II, $Np^2 = 5 \times 10^{16}$, < 1 year running
 - Develop detectors
 - Calorimeters for decay electrons, very high rates
 - Time scale: J-PARC letter of intent for muon EDM submitted last year. Deuteron EDM experiment design under way - PRISM II and beam line studies and efforts to obtain funding continuing.

- Minimum pulse spacing 500 μs , to allow time for muons to decay
- Pulsed beam, many pulses preferred
- $p \approx 300 - 500 \text{ MeV}/c$, $\frac{\Delta p}{p} < 2\%$, 800 π m.m. mrad in x and y

Muon Beam Requirements

- Pulsed beam needed
- \rightarrow needed flux, $NP^2 \approx 5 \times 10^{16}$, in 10^7 seconds
- At $p = 0.5$ GeV/c, $P = 0.60$
- $\frac{d}{dp} = 30\% \rightarrow 2\%$
- superconducting version: $B=2.8$ T, $r=10$ m
- normal version: $B=1.8$ T, $r=21$ m
- phase rotator, no pion contamination
- Muon momentum compression: **Fixed Field Alternating Gradient**
- Muon momentum selection
- Pion decay and muon transport: $B=1$ T, $r=45$ cm x $L=20$ m
- $R=5$ m, $\text{arc} = 50^\circ$
- Pion momentum selection (curved solenoid) $B=1$ T, $r=45$ cm x $r=10$ cm-45 cm x $L=450$ cm
- Semi-adiabatic transfer to lower solenoid field: $B=6$ T \rightarrow 1 T,
- Pion capture: High-field solenoid: $B=6$ T, $r=10$ cm x $L=120$ cm

- Increased intensity ($2 \text{ MW} \rightarrow 10 \text{ MW} \rightarrow ?$)
- Cooled beams

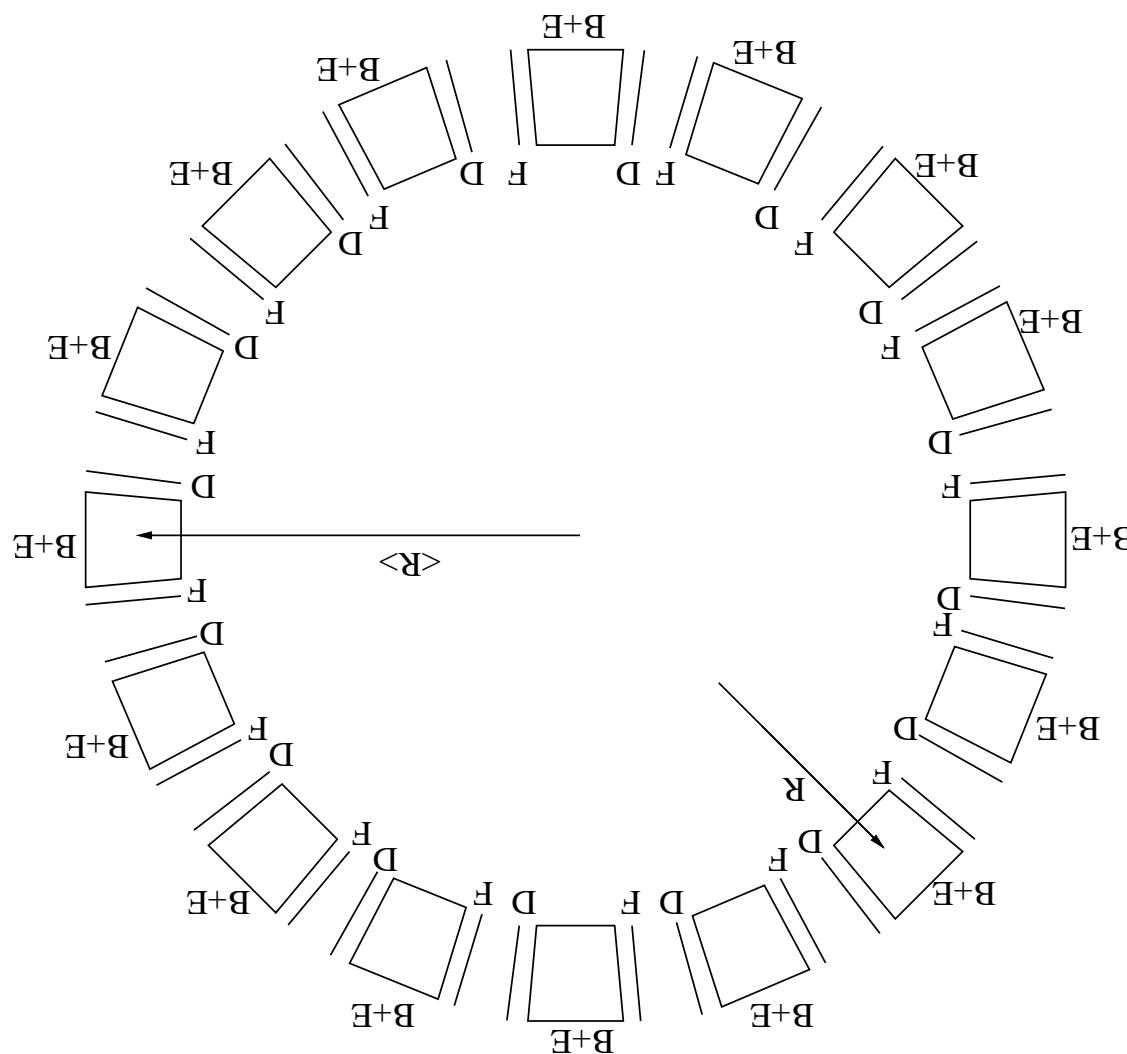
To get to $d_\mu \sim 10^{-26} \text{ e.cm....}$

Measurement is intensity limited

Muon Detectors

- Calorimeters for muon-decay electron showers above and below stored beam-
- Must be stable over very wide range of rates from early to late muon decay times - rates at early times very high.
- Straight sections in ring needed for placement of left-right calorimeters (systematic studies of plane of $(g-2)$ precession)
- Anticipated high rates, esp. in a 10^{-26} e-cm measurement, integrate detectors signals, instead of single pulses

$$\text{Signal: } R_E(t) = \frac{E_{up}(t) + E_{down}(t)}{E_{up}(t) - E_{down}(t)}$$



Proposed EDM ring- Preliminary Design

$p = 0.5 \text{ GeV/c}$
 $B_z = 0.25 \text{ T}$
 $E_r = 2 \text{ MV/m}$
 $R = 7 \text{ m}$
 $\langle R \rangle = 11 \text{ m}$
 $B+E = 2.6 \text{ m}$
Intervals = 1.7 m

- $d_u \approx 10^{-24} e \cdot cm$ (and $d_{deuteron} < 10^{-27} e \cdot cm$): exceptional physics reach
- Deuteron EDM experiment being designed and developed now-most systematic problems for muons will be solved in developing this experiment. Begins 4 years after funding, runs for two years.
- Techniques perfected for deuteron will carry over to the muon case in the future
- Proton Driver has the potential to provide the needed muon flux (LO's submitted to J-PARC for Muon EDM and PRISM II)
- At $10^{-24} e \cdot cm$ muon EDM is statistics limited- with increases in muon flux, go to $10^{-26} e \cdot cm$ or better

Conclusions